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Four pulsar discoveries in NGC 6624 by TRAPUM using MeerKAT

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ABSTRACT

We report four new pulsars discovered in the core-collapsed globular cluster (GC) NGC 6624 by the TRAPUM Large Survey Project with the MeerKAT telescope. All of the new pulsars found are isolated. PSR J1823−3021I and PSR J1823−3021K are millisecond pulsars with period of respectively 4.319 and 2.768 ms. PSR J1823−3021J is mildly recycled with a period of 20.899 ms, and PSR J1823−3022 is a long period pulsar with a period of 2.497 s. The pulsars J1823−3021I, J1823−3021J, and J1823−3021K have position and dispersion measure (DM) compatible with being members of the GC and are therefore associated with NGC 6624. Pulsar J1823−3022 is the only pulsar bright enough to be re-detected in archival observations of the cluster. This allowed the determination of a timing solution that spans over two decades. It is not possible at the moment to claim the association of pulsar J1823−3022 with the GC given the long period and large offset in position (∼3 arcmin) and DM (with a fractional difference of 11 percent compared the average of the pulsars in NGC 6624). The discoveries made use of the beamforming capability of the TRAPUM backend to generate multiple beams in the same field of view which allows sensitive searches to be performed over a few half-light radii from the cluster centre and can simultaneously localize the discoveries. The discoveries reflect the properties expected for pulsars in core-collapsed GCs.

Key words: stars: neutron – pulsars: general – globular clusters: individual: NGC 6624.

1 INTRODUCTION

NGC 6624 is a globular cluster (GC) located in the bulge close to the Galactic centre (Galactic coordinates $l = 2^\circ.78$, $b = -7^\circ.91$) at a distance from the Sun of 8.0 ± 0.1 kpc (Baumgardt & Vasiliev 2021) and a Galactocentric radius of 1.2 kpc.[1] The stellar distribution in the central regions of the GC is not flat but shows a 'cusp' that is typical of systems that have undergone core collapse (Sosin & King 1995; Noyola & Gebhardt 2006).

This GC is known to contain eight pulsars (Biggs et al. 1994; Lynch et al. 2012; Ridolfi et al. 2021) of which six are millisecond pulsars (MSPs) and two long-period pulsars. Only two pulsars J1823−3021F and J1823−3021G are known to be part of binary systems. J1823−3021G is a binary pulsar in an eccentric orbit typical of an exchange encounter that has the potential of being one of the most massive known pulsars (Ridolfi et al. 2021). Two pulsars have long spin periods, J1823−3021B has a period of 378.59 ms and J1823−3021C has a period of 405.93 ms. Both have short characteristic ages, respectively, 190 and 30 Myr, which is at odds with the regular pulsar formation scenario. The pulsars should have formed recently but the lack of star formation in this globular cluster in the last few Gyr implies that no massive stars were around to form them. This could suggest that these pulsars were old, unrecycled NSs that were, thanks to exchange encounters, incorporated in X-ray binaries, where they started being spun up by accretion of matter from their new companions. Because of the high stellar densities in these clusters, these X-ray binaries were disrupted before the pulsar's magnetic field decreased to the typical values observed in 'fully

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[1]A list of the structural parameters of GCs is available at the website (Credits: Holger Baumgardt with help from Sam Hinton): https://people.smp.uq.edu.au/HolgerBaumgardt/globular/parameter.html

recycled' MSPs (Verbunt & Freire 2014). Alternative formation scenarios have been put forward to explain the presence of such pulsars like accretion-induced collapse, direct collisions with a main sequence star (Lyne, Manchester & D'Amico 1996), or electron capture supernova of an OMgNe white dwarf (Boyles et al. 2011).

The isolated MSP J1823−3021A also has a very high spin period derivative, and also a small characteristic age of 25 Myr. It was suggested that the period derivative is heavily influenced by the gravitational potential of the GC and that it could be a sign of the presence of an intermediate mass black hole in the centre of NGC 6624 (Perera et al. 2017a,b). However, the pulsar also shows remarkably strong gamma-ray flux implying that a significant fraction of the spin-down must be intrinsic and the magnetic field has to be considerably higher than that of the average MSP (Freire et al. 2011). A higher number of pulsars close to the cluster centre would allow us to test whether an intermediate mass black hole is really present.

The properties of the pulsars in NGC 6624 are quite different from the typical GC but are similar to those GCs that have undergone core-collapse. Verbunt & Freire (2014) have shown that this difference can be quantified by the encounter rate for a single binary in the GC which represents the likelihood of any particular binary system to undergo dynamical encounters; this is ∼4 times higher for core collapsed clusters than non-collapsed clusters. GCs with high values of this parameter usually show a larger fraction of isolated pulsars, pulsars with longer spin periods, pulsars distributed over large radii outside of the core, and binaries produced in exchange encounters.

The high value of the encounter rate of this GC (the ninth highest of all the Galactic GCs and ∼ 1.1 times the value of 47 Tucanae; Bahramian et al. 2013) suggests that a larger population of pulsars is still undiscovered in this GC, while the high encounter rate per binary (second highest within all GCs with 3 or more known pulsars and ∼6 times the value of 47 Tucanae; Verbunt & Freire 2014) suggests the new discoveries might have gone through dynamical interactions like exchange encounters that could form exotic objects such as eccentric double neutron star systems. For these reasons, NGC 6624 was considered as a high priority target in the pulsar searches in GCs with the MeerKAT radio telescope in South Africa (Jonas & MeerKAT Team 2016; Camilo et al. 2018). Two of the Large Survey Projects (LSP) that are observing with the telescope, MeerTime[2] (Bailes et al. 2016, 2020) and TRansients And PUlsars with Meerkat (TRAPUM)[3] (Stappers & Kramer 2016) have the search and timing of pulsars in GCs as one of the science goals. Together the two projects have discovered more than 40 new pulsars in GCs.[4]

Given the scientific overlap, the two projects have decided to share resources and observing time. The collaboration has already resulted in two publications regarding NGC 6624: a detailed study of the giant pulses from J1823−3021A (Abbate et al. 2020) and the discovery of two new MSPs (Ridolfi et al. 2021) in this cluster. The massive eccentric binary J1823−3021G discovered in the latter work is an example of the interesting new pulsars still to be discovered. These results were obtained using observations taken with the Pulsar Timing User Supplied Equipment (PTUSE) machines made available by MeerTIME with data from only the central 44 antennas of the 64 available. This number was chosen so that the maximum baseline would be below 1 km and the tied array beam would be large enough to cover the central regions of the cluster. The observations were carried out at *L*-band (856–1712 MHz) and the tied array beam had a radius of ∼0.5 arcmin.

In this paper, we present the observations and discoveries made using the Filterbanking Beamformer User Supplied Equipment (FBFUSE) and Accelerated Pulsar Search User Supplied Equipment (APSUSE) backend provided by TRAPUM. Together these machines are able to synthesize and record of the order of 500 coherent beams for use in pulsar and fast transient searching. Using all of the available antennas it is possible to cover, with a large number of small tied-array beams, an area as large as 1–4 arcmin in radius depending on the configuration (Chen et al. 2021). This is enough to extend up to more than twice the reported half-light radius of the GC of ∼1 arcmin (Baumgardt & Hilker 2018). The sensitivity is ∼1.5 times higher when compared with the previous PTUSE observations in the centre of the GC and it gets increasingly higher the further away we look. The area that can be searched is also larger allowing for further discoveries in this GC.

2 TRAPUM OBSERVATIONS

The observations performed with the FBFUSE and APSUSE machines of TRAPUM that have been searched for new pulsars were performed using 60 antennas in *L*-band (856–1712 MHz) on 2020 May 21 and August 11. In both observations we synthesized 288 coherent beams. The beam shape depends on the exact configuration of the antennas and position in the sky, we can estimate its size with an elliptical fit. In both observations the semimajor axis of the elliptical fit at 50 percent of the power is 17 arcsec at the central frequency of 1284 MHz and semiminor axis is 10 arcsec. In the first observation, the average overlap fraction between neighbouring beams at the central frequency was ∼0.8 resulting in a total area covered of ∼2.6 arcmin in radius from the centre. For the second observation the overlap was set at ∼0.7 and the area covered was increased to ∼3.1 arcmin in radius. The tiling pattern of the two observations was determined using the software MOSAIC[5] (Chen et al. 2021) and is shown in Fig. 1. In both cases, the observation length was 4 h. The first observation was already described in Ridolfi et al. (2021) and was used to localize the known pulsars.

The total intensity data from each coherent beam was recorded in filterbank mode with a time resolution of 76 μs and a bandwidth of 856 MHz, centred around 1284 MHz and divided into 4096 channels. After the observation was concluded, the data were incoherently de-dispersed at the dispersion measure (DM) of 86.88 pc cm^{-3}, corresponding to the DM of J1823−3021A located near the centre of the cluster as measured by MeerKAT observations in the same band (Abbate et al. 2020). The Inter-Quartile Range Mitigation algorithm[6] (Morello, Rajwade & Stappers 2022) was applied to filter out the brightest Radio Frequency Interference (RFI) and the channels were averaged by a factor of 16 resulting in 256 channels across the full bandwidth to reduce disc usage.

Most of the known pulsars in NGC 6624 have DMs between 86.2 and 87.0 pc cm^{-3} with the exception of J1823−3021E that has a DM of 91.4 pc cm^{-3}. We decided to search for pulsars between a DM of 80 and 95 pc cm^{-3} with a DM step size of 0.05 pc cm^{-3} to allow for a greater spread in DM in the potential candidates. Given the reduced number of channels, the pulse of a potential pulsar will

[2] http://www.meertime.org

[3] http://www.trapum.org

[4] An up-to-date list of the new pulsars discovered can be seen at (Credits: Ewan Barr): http://www.trapum.org/discoveries/

[5] https://github.com/wchenastro/Mosaic

[6] https://github.com/v-morello/iqrm

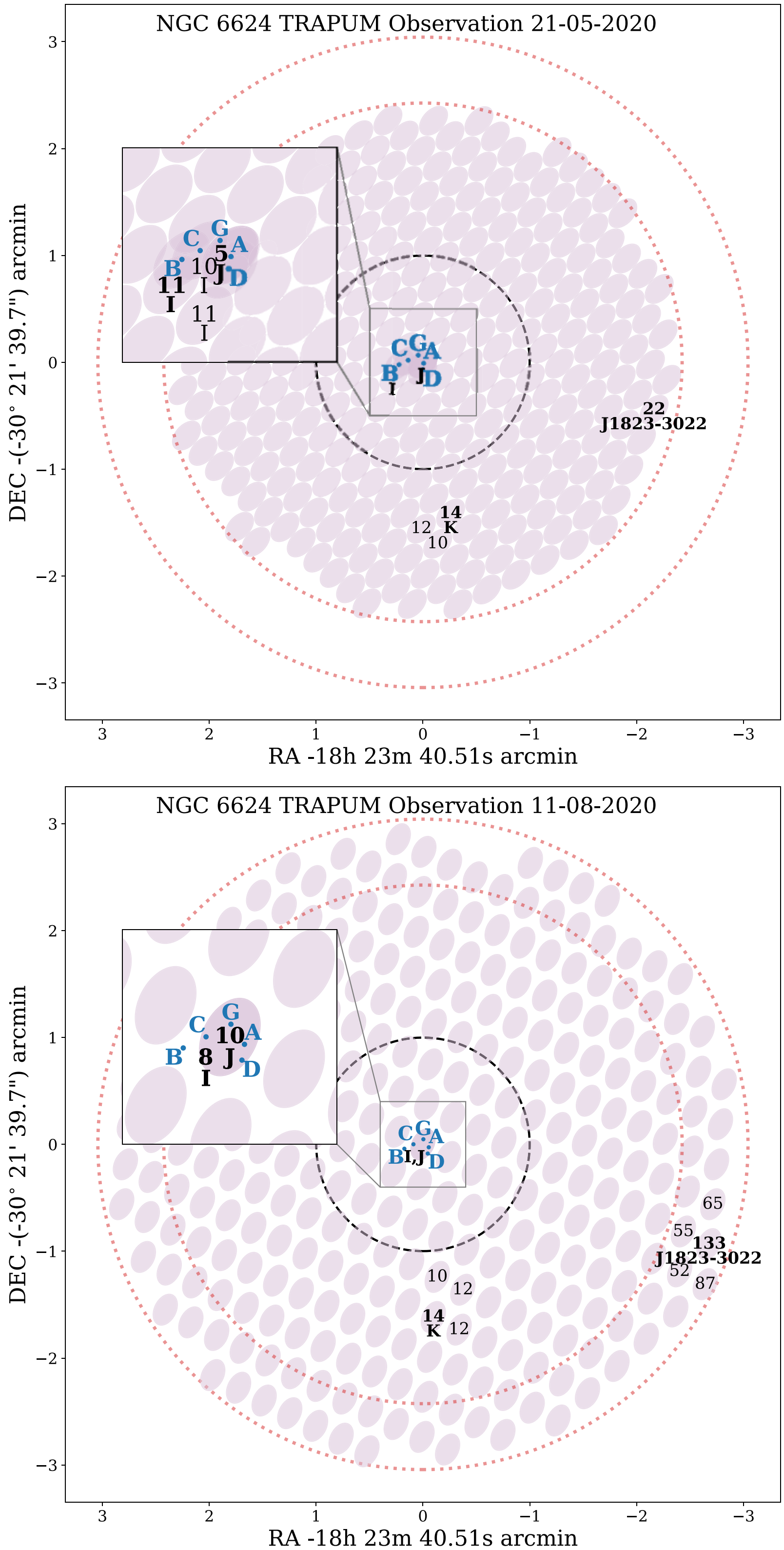

Figure 1. Tiling pattern of the beams of the TRAPUM observations of NGC 6624 performed on 2020 May 21 (top) and August 11 (bottom). The light pink ellipses show the single beams up to 80 percent of the boresight power. The blue dots are the pulsars with precisely known positions. The black dashed circle shows the half-light radius of the cluster, ∼1 arcmin (Baumgardt & Hilker 2018). The red dotted circles are the maximum extent of the size of the tiling in the two observations plotted for comparison. The value of the S/N of the detection of the new pulsars are reported in each beam where the pulsars are seen with the highest value reported in bold. All of the beams shown have been searched for new pulsars.

be affected by smearing if the DM does not match the value applied during de-dispersion of 86.88 pc cm^{-3}. The smearing caused by the DM in the worst affected channel goes from 0.3 ms for a DM of 80 pc cm^{-3} to 0.4 ms for a DM of 95 pc cm^{-3}. This effect will reduce the sensitivity of our search for rapidly spinning pulsars if the DM is far from the value chosen before reducing the number of channels.

The searching procedure was carried out using PULSAR_MINER[7] based around the PRESTO pulsar searching package (Ransom, Eikenberry & Middleditch 2002) and described in detail in Ridolfi et al. (2021). The beams were searched for both isolated and binary pulsars by performing a search in Fourier space. In the case of binary pulsars, the acceleration along the line of sight, a_l, shifts the observed spin frequency of a potential pulsar over the length of the observation, $t_{\rm obs}$, by a number of $z = t_{\rm obs}^2 a_l / cP$ Fourier bins, where c is the speed of light and P is the period of the potential pulsar. The search is performed up to a maximum of $z_{\rm max}$ of 200. This type of search is effective as long as the acceleration remains constant over the observation which is a reasonable assumption if $t_{\rm obs} \lesssim 0.1 P_{\rm b}$, where $P_{\rm b}$ is the orbital period (Ransom, Cordes & Eikenberry 2003). In order to search for binary pulsars with short orbital periods, we split the observation into segments of 60 and 20 min and repeated the search in each segment. This strategy allowed us to be sensitive to pulsars in orbits longer than ∼200 min.

Of all the candidates that were found in the search only the ones with a Fourier significance of more than 4σ in adjacent DM trials were kept. After removing harmonically related candidates and periodic RFI, the remaining candidates were visually inspected. In order to confirm that the candidates found are real pulsars, we checked if the same candidate appears in neighbouring beams of the same observation or in beams pointing in the same direction in both observations. Additionally, for the most interesting candidates, we folded the corresponding beam of the other observation at the period and DM of the candidate for further confirmation. After a candidate has been confirmed, we derived an approximate ephemeris based on the detection, folded the observation using the DSPSR[8] pulsar package (van Straten & Bailes 2011) and run the PDMP routine of PSRCHIVE[9] (Hotan, van Straten & Manchester 2004; van Straten, Demorest & Oslowski 2012) to improve the quality of the detection. To obtain the best value of DM we first averaged the frequency channels of the best detection from 256 to 8 and extracted times-of-arrival (ToAs) at each channel with the PAT routine of PSRCHIVE using a single template. We used TEMPO2[10] (Hobbs, Edwards & Manchester 2006) to fit these ToAs leaving the DM as the only free parameter.

Finally, the flux density of the pulsars was measured using the radiometer equation (Lorimer & Kramer 2012):

$$S = ({\rm S/N})_{\rm best} \frac{T_{\rm sys}}{G\sqrt{n_p t_{\rm obs} \Delta f}} \sqrt{\frac{W}{P - W}}, \qquad (1)$$

where (S/N)$_{\rm best}$ is the signal-to-noise ratio (S/N) of the best detection of the pulsar, $T_{\rm sys}$ is the system temperature of the telescope taken to be 26 K for the observations,[11] $G = (N_{\rm ant}/64) \times 2.8$ K Jy^{-1} is the gain of the telescope and depends on $N_{\rm ant}$ the number of antennas used in the observation, $n_p = 2$ is the number of polarizations summed, $t_{\rm obs}$ is the length of the observation, Δf is the effective bandwidth taken to be 700 MHz after the RFI cleaning and P is the period of the pulsar. W is the equivalent width of the pulse defined as the width of a top-hat function with the same height and same total area as the pulsar profile.

[7] https://github.com/alex88ridolfi/PULSAR_MINER

[8] http://dspsr.sourceforge.net

[9] http://psrchive.sourceforge.net

[10] https://bitbucket.org/psrsoft/tempo2/

[11] https://skaafrica.atlassian.net/rest/servicedesk/knowledgebase/latest/articles/view/277315585

3 DISCOVERIES

Four new pulsars were discovered of which three can safely be considered members of the GC. The profiles of the new discoveries are shown in Fig. 2 while the period, position, values of DM and flux density are shown in Table 1 and in Fig. 3.

3.1 J1823−3021I

PSR J1823−3021I is an isolated MSP with a rotational period of 4.319 ms and DM of 87.31 pc cm^{-3}. The profile has a single component with equivalent width of 0.61 ms. It was detected by the pipeline in the first observation in the central beam and in two neighbouring beams south of the centre. After folding the second observation at the discovery period and DM, the pulsar showed up in the central beam.

The position near the centre of the cluster and the value of the DM which is compatible with the other pulsars suggest that this new discovery is associated with the cluster.

3.2 J1823−3021J

PSR J1823−3021J is another isolated pulsar. It has a rotational period of 20.899 ms, DM of 86.82 pc cm^{-3} and was found in the central beam of the second observation. The profile has a single component with equivalent width of 1.96 ms. It was confirmed after folding the central beam of the first observation at the discovery period and DM.

The DM is compatible with the other known pulsars and it is located in the core of NGC 6624, this suggests that this pulsar is a member of the cluster. Its rotational period is higher than what we would expect for MSPs if the recycling process was allowed to continue uninterrupted. A possible explanation is that the binary was disrupted by a dynamical interaction during the accretion phase. These types of pulsars are known to be present not only in NGC 6624 (B and C), but also in several other GCs with high encounter rate per binary like e.g. M 15, NGC 6440, NGC 6441 (Freire et al. 2008) and NGC 6517 (Lynch et al. 2011; Pan et al. 2021).

3.3 J1823−3021K

PSR J1823−3021K is the third new isolated pulsar we found in the cluster. It has a rotational period of 2.768 ms and a DM of 87.50 pc cm^{-3}. It has a single broad component with equivalent width of 0.89 ms. It was found in a beam of the first observation distant ∼1.4 arcmin from the centre and in two neighbouring beams with lower S/N. It was also found by the pipeline in the four beams of the second observation corresponding to the same location. It is the most rapidly spinning known pulsar in this GC.

This pulsar is located at about ∼1.4 arcmin from the centre at about ∼1.4 times the half-light radius. Given that the DM is close to the rest of the known pulsars and that it is an isolated MSP, it is reasonable to assume that it is a member of NGC 6624.

3.4 J1823−3022

PSR J1823−3022 is an isolated bright pulsar with a period of 2.4978 s and a DM of 96.7 pc cm^{-3}. It has a single component with equivalent

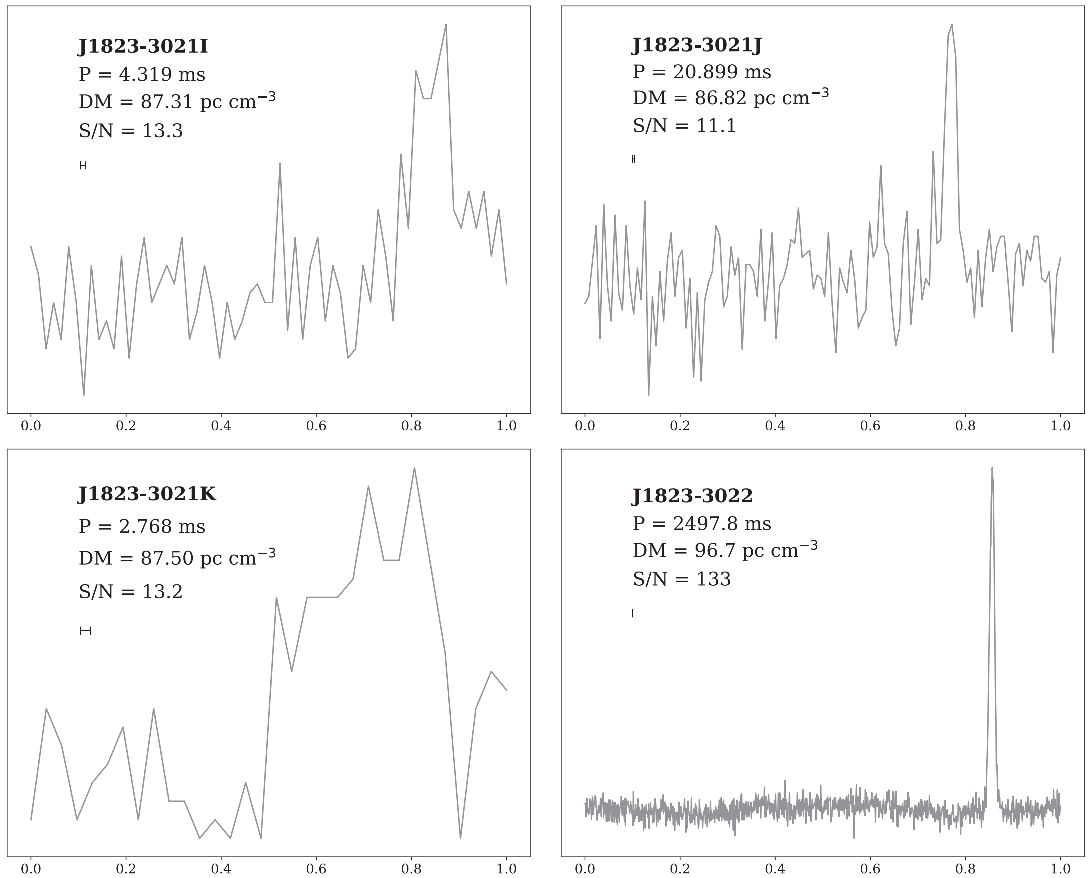

Figure 2. Profiles of the four pulsars discovered in the TRAPUM observations of NGC 6624. The name, period, and DM for each pulsar are reported in each plot. The bar under the DM shows the quadrature sum of the time resolution of 76 μs of the observations and the DM smearing in the worst affected channel in comparison to the period of the pulsars. The profile of J1823−3022 shows variations of the baseline that are caused by broad-band RFI.

Table 1. Properties of the newly discovered pulsars in the observations of NGC 6624. We report the barycentric period, DM, position, and flux density derived from the radiometer equation. For pulsars I and K, we report the position found using the SEEKAT software. For pulsar J the software could not be used and we report the position of the beam at the centre of the cluster were the pulsar was found. For pulsar J1823−3022 we report the position derived by timing. Numbers in parentheses represent 1-σ uncertainties in the last digit.

Summary of discoveries						
Pulsar name	Type	P (ms)	DM (pc cm^{-3})	α_{J2000}	δ_{J2000}	S_{1300} (μJy)
NGC 6624I	Isolated	4.319	87.31(4)	$18^h23^m40^s.6(2)$	$-30^\circ21'40''(3)$	11.7
NGC 6624J	Isolated	20.899	86.82(7)	$18^h23^m40^s.5(6)$	$-30^\circ21'39''(14)$	7.7
NGC 6624K	Isolated	2.768	87.50(7)	$18^h23^m39^s.4(3)$	$-30^\circ23'07''(5)$	19.7
J1823−3022	Isolated	2497.8	96.7(2)	$18^h23^m27^s.27(1)$	$-30^\circ22'35''(2)$	41

width of 49 ms. It was found near the edge of the tiling of the second observation appearing brightest in the beam on the edge of the tiling and, with lower S/N, in four surrounding beams. This position was not covered in the tiling of the first observation but the pulsar still appears by folding at the discovery period and DM in one beam of the first observation as shown in Fig. 1. The pulsar was so bright that it was possible to see single pulses coming from the pulsar. We detected 27 single pulses with S/N higher than 7 corresponding to 0.5 percent of all the rotations of the pulsar over the course of 4 h of observations.

The pulsar was found with the highest S/N in a beam at the edge of the tiling. It is possible, therefore, that the true position is further away from the cluster centre than we measured. In order to localize the source we made an additional observation on 2021 November 7 using only 38 antennas in L-band and forming only 17 beams with an average overlap at the central frequency of ∼ 0.7 around the position of the beam with the highest S/N as shown in Fig. 4. The pulsar was detected in all of the beams of this observation but also in this case the beam with the highest S/N was the furthest from the centre along the edge of the tiling.

Using the detected period and provisional position, we folded archival observations of the cluster made over the years with MeerKAT, the Parkes radio telescope, and the Green Bank Telescope (GBT). Previous MeerKAT observations carried out with the PTUSE backend had a tied array beam of just ∼0.5 arcmin while the pulsar appears to be located at ∼3 arcmin. Despite this, the pulsar was

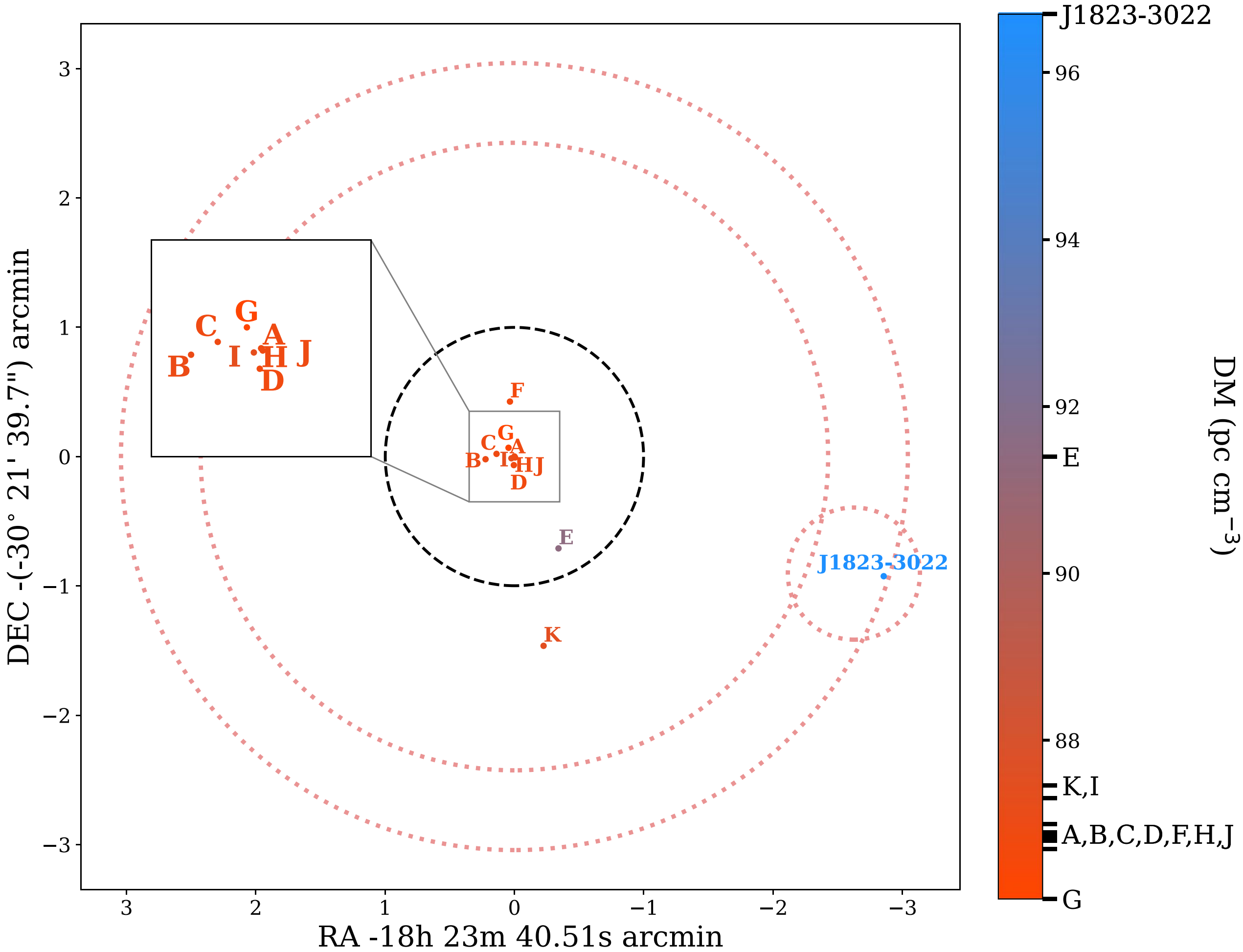

Figure 3. Map of the cluster NGC 6624 with all the known pulsars. The previously known pulsars are marked with a blue letter while the new discoveries are shown in black. The black dashed circle shows the half-light radius of the cluster while the red dotted curves show the extension of the tiling of the three observations as in Fig. 1 and in Fig. 4. The colour of the pulsars represents the value of DM according to the colour bar at the right of the plot. Of the new discoveries, pulsar J1823−3021I and K have been localized using SeeKAT and J1823-3022 with timing.

detected in an observation made at UHF-band (550–1050 MHz) where the beam size is significantly larger. We were able to detect the pulsar in an observation at Parkes from 1999 using the Analog Filterbank in the frequency range 1240–1497 MHz and in a recent one from 2019 using the Pulsar Digital Filterbank 4 in the same frequency range. We were also able to detect the pulsar in observations taken around 2009 at the GBT with the GUPPI backend in the frequency range 1600–2400 MHz and in a set of observations taken around 2020 using the VEGAS backend both in the frequency range 1100–1900 MHz and in the frequency range 1600–2400 MHz. This was possible because the beams of Parkes and GBT in the sky are large enough to cover the position of J1823−3022. The pulsar was not detected sooner in these observations likely because of the bright broad-band RFI that appear at these long periods. These RFI can also be seen in the TRAPUM observations and cause the variations in the baseline of the profile shown in Fig. 2.

Thanks to these detections, we were able to determine a phase-connected timing solution for J1823−3022 that spans over two decades from 1999 to 2022. The timing solution is shown in Table 2 and the residuals of the ToAs are shown in Fig. 5. The position found coincides with the beam with highest S/N in the observation of 2021 November 7 as shown by the black ellipse in Fig. 4.

The position of the pulsar derived by timing places it at 2.99 arcmin from the centre or ∼3 times the half-light radius of the cluster. This is almost twice the half-mass radius of ∼1.58 arcmin (Baumgardt & Hilker 2018), but still inside the estimated tidal radius of the cluster, corresponding to ∼8.33 arcmin.[12] The presence of pulsars so far from the centre of a GC is rare but a few exceptions are known in other core collapsed clusters like B1718-19A (Lyne et al. 1993), located ∼2.6 half-mass radii from the centre, J1911-5958A (D'Amico et al. 2001), distant ∼1.4 half-mass radii from the centre, and J1801-0857D, located ∼1.4 (Lynch et al. 2011) half-mass radii from the centre.

The DM is ∼10 pc cm^{-3} higher than the average DM value than for the pulsars located in the centre of the GC and significantly higher than the rest of the known pulsars. It is outside the range of DM initially searched but it was still detected thanks to its slow period. The incorrect DM causes a delay in the arrival times of the pulse at different frequencies that is in the order of 5 ms for every unit of DM in *L*-band. This is smaller than the pulse width of the new

[12]calculated using equation (8) of Webb et al. (2013) using data from Baumgardt et al. (2019). For details see: https://people.smp.uq.edu.au/HolgerBaumgardt/globular/parameter.html

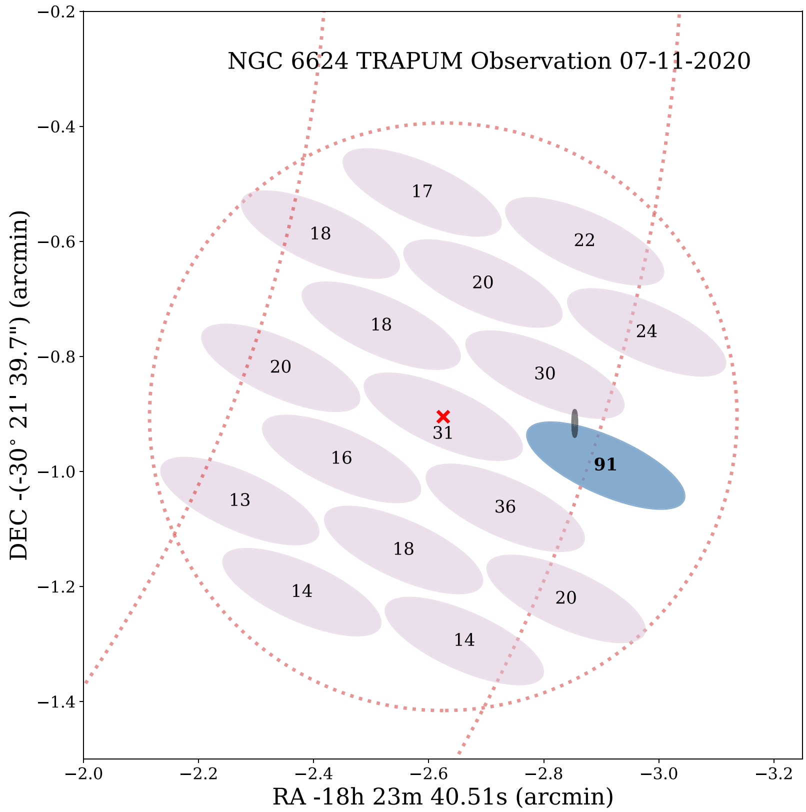

Figure 4. Tiling pattern of the beams of the TRAPUM observations of NGC 6624 performed on 2021 November 7 in order to localize J1823−3022. The light pink ellipses show the single beams up to 84 per cent of the boresight power. The red cross marks the position of the detection with highest S/N of J1823−3022 in the previous observations. The number in each beam represents the value of the S/N of the detection. The beam with the highest S/N is highlighted in blue. The red dotted circles are the maximum extent of the size of the tiling in this and the two previous observations plotted for comparison. The black ellipse shows the position of J1823−3022 as determined by the timing. The size of ellipse represents the 1σ uncertainty on the position.

Table 2. Timing solution for J1823−3022 as derived from the timing of the observed ToA with TEMPO2. The time units are TDB, the adopted terrestrial time standard is TT(TAI) and the Solar System ephemeris used is JPL DE421 (Folkner, Williams & Boggs 2009). Numbers in parentheses represent 1-σ uncertainties in the last digit.

Pulsar	J1823−3022
R.A. (J2000)	18:23:27.27(1)
DEC. (J2000)	−30:22:35(1)
Spin Frequency, f (s^{-1})	0.400354407801(6)
1st Spin Frequency derivative, $\dot{f}$ (Hz s^{-1})	$-1.3021(2) \times 10^{-16}$
Reference Epoch (MJD)	59072.811
Start of Timing Data (MJD)	51409.581
End of Timing Data (MJD)	59580.786
Dispersion Measure (pc cm^{-3})	96.7(2)
Number of ToAs	86
Weighted rms residual (μs)	2319
S_{1300} (mJy)	0.039
Derived parameters	
Spin Period, P (s)	2.49778691208(4)
1st Spin Period derivative, $\dot{P}$ (s s^{-1}) ...	$8.123(1)\times 10^{-16}$
Surface Magnetic Field, B_0, (G)	1.44×10^{12}
Characteristic Age, τ_c (Myr)	48.75

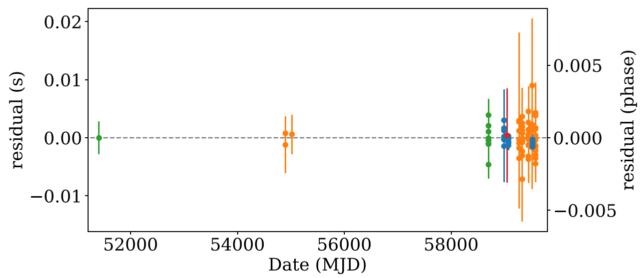

Figure 5. Timing residuals of J1823−3022 as a function of time. The points in blue represent the ToAs obtained from TRAPUM observations at MeerKAT, the red point is from a PTUSE observation at MeerKAT, the orange points are from GBT observations, and the green points from observations at Parkes.

discovery and therefore does not impact the detectability. Such a high difference in DM has only been seen in two GCs, Terzan 5 and NGC 6517 but in both cases the central value of DM is more than twice that of NGC 6624.

The DM distribution of the known pulsars in the GC is shown in Fig. 3. Most of the pulsars have DM within 86 and 88 pc cm^{-3} while J1823−3021E has a DM significantly higher than the rest at 91.4 pc cm^{-3}. J1823−3021E is certainly associated with the cluster given that it is an isolated MSP and is located within the half-light radius. We can conclude that the intervening medium along the line of sight can change the DM of the order of 4 pc cm^{-3} over a distance

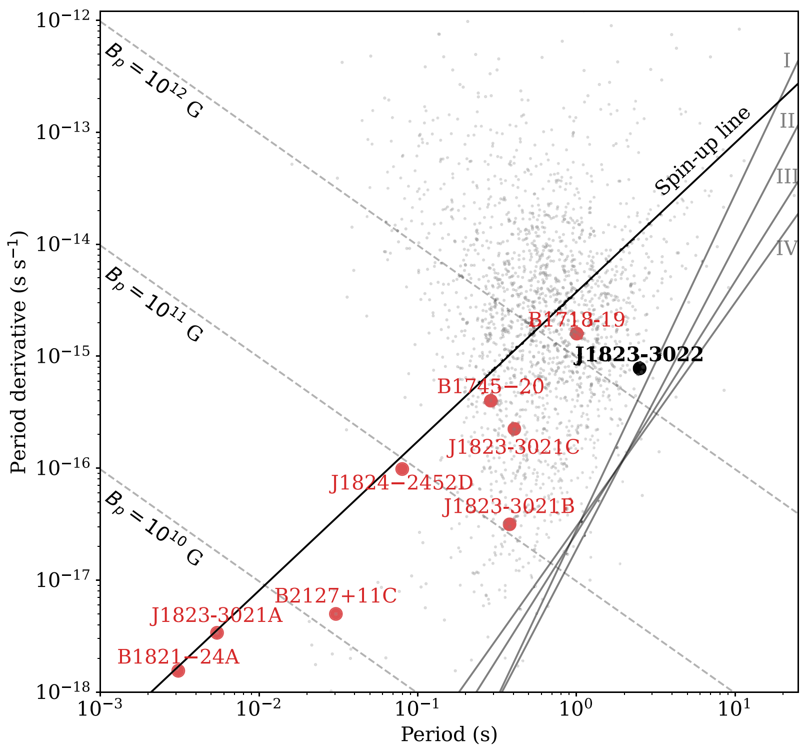

Figure 6. *P*-$\dot{P}$ diagram showing the measured period derivative of J1823−3022 (black). The plot shows lines of constant magnetic field, the spin-up line as adjusted by Verbunt & Freire (2014) to fit B1821−24A and J1823−3021A, and four models of the death line marked from I to IV following Cruces et al. (2021). The pulsars associated with GCs with the highest magnetic fields are plotted in red for comparison, for these the effect of the cluster acceleration on the measured $\dot{P}$ is significantly smaller than the intrinsic $\dot{P}$. These pulsars were likely old, unrecycled NSs within the clusters that have recently (within the last 2 per cent of the age of the cluster, as inferred from their characteristic ages) gone through a recycling episode, hence their location below the spin-up line. This was then interrupted by further stellar interactions, otherwise they would have become 'normal' MSPs in the lower left-hand side of the diagram; this is consistent with the fact that we only see these systems in GCs with very high interactions rates per binary. The position of J1823−3022 in this diagram is consistent with this hypothesis, but also with it being an unassociated, normal pulsar in the background (grey dots); these represent all the pulsars present in the PSRCAT catalogue (version 1.66; Manchester et al. 2005). Note the presence of at least three, possibly four systems, associated with NGC 6624 in this plot.

of ∼ 1 arcmin. This intervening medium can either be located inside the cluster or in the Galaxy along the line of sight. Applying this argument to J1823−3022 we can conclude the DM excess of ∼10 pc cm^{-3} over 3 arcmin could be explained by foreground material and that the pulsar could be part of the cluster. Alternatively we can look at a Galactic model of electron density distribution to estimate the distance of this pulsar based on the value of DM. Using the models NE2001 from Cordes & Lazio (2002) and YMW16 from Yao, Manchester & Wang (2017) we find that the cluster should be located at 2.4 kpc according to NE2001 (3.1 kpc according to YMW16) and the pulsar J1823−3022 at 2.6 kpc (3.8 kpc). This would imply that J1823−3022 is 0.2 kpc (0.7 kpc) further than the centre of the cluster. However, the distance to the cluster estimated this way is a factor of 3 (2) smaller than the distance of the cluster of 8.0 kpc measured from spectroscopy and kinematics (Baumgardt & Vasiliev 2021). This implies that the electron density models largely underestimate the distances along this line of sight and are therefore not reliable regarding the position of J1823−3022.

The period of 2.497 s is very long for a GC pulsar and more typical for Galactic disc pulsars. The slowest pulsar known to be associated with a GC is B1718-19A with a period of 1.002 s (Lyne et al. 1993). It must be stated, however, that the GC NGC 6624 already has two other long period pulsars suggesting that apparently young pulsars are able to survive in the cluster.

The period derivative measured through timing of J1823−3022 is $8.123 \pm 0.001 \times 10^{-16}$ s s^{-1}. This corresponds to a surface magnetic field of 1.44×10^{12} G and a characteristic age of ∼50 Myr. The corresponding position in the *P*-$\dot{P}$ diagram is shown in Fig. 6. If the pulsar is associated with the GC it would be the strongest magnetic field measured in a GC pulsar but still close to that of B1718-19A that has a magnetic field of 1.26×10^{12} G (Lyne et al. 1993). The small characteristic age suggests that J1823−3022 is either very young or the recycling process stopped recently. If the pulsar is part of the cluster and the recycling process was stopped by a dynamical encounter that also displaced the pulsar, it would also explain the large positional offset as it would not have had time to sink back in the core. Similarly, if the pulsar was born recently after an accretion-induced collapse or an electron capture supernova, it could have been displaced by a kick.

If the pulsar has gone through a recycling episode in the recent past, it should be located below the spin-up line in the *P*-$\dot{P}$ diagram (Verbunt & Freire 2014). This line corresponds to the shortest period that can be reached during the recycling process by accretion at the Eddington limit on the pulsar (see Pringle & Rees 1972):

$$P_{\rm min} \simeq 1.3\ {\rm s} \times \left(\frac{\rm B}{10^{12}\ {\rm G}}\right)^{6/7} \simeq 1.6\ {\rm s} \times (10^{15}\dot{P})^{3/4}, \quad (2)$$

where we used $({\rm B}/10^{12})^2 \simeq 10^{15} P\dot{P}$. Considering the uncertainties in the models behind equation (2), an alternative spin-up line where $\dot{\rm P}$ is seven times higher for the same *P* has been suggested (Verbunt

& Freire 2014). All of the pulsars with high magnetic field strengths in GCs lie below such a line in the P-$\dot{P}$ diagram. This line is shown in Fig. 6 alongside some of the pulsars associated with GCs with the highest magnetic fields. J1823−3022 is well below this line making it possible that it has gone through a recent recycling episode. However, the period derivative of this pulsar is similar to that of young Galactic pulsars with similar periods. Based on this parameter we cannot say whether it is associated with the cluster or not.

If the pulsar is not associated we can estimate the probability of it being aligned along the same line of sight. The number of known pulsars in an area of 10 degrees in radius surrounding the cluster according to the PSRCAT catalogue[13] (version 1.66; Manchester et al. 2005) is 147. The probability of finding one within 3 arcmin is ∼0.003 corresponding to about 3σ. Of all of them only nine have a DM within 10 pc cm^{-3} of the central value of NGC 6624. However, it must be noted that the pulsars in the PSRCAT catalogue are significantly brighter than the newly discovered pulsar so this should be considered as a lower limit to the probability.

4 LOCALIZATION

The small size of the beams in the TRAPUM observations can determine the position of the newly discovered pulsars with a precision of 10–20 arcsec. If the new discovery has been detected in more than one beam, it is possible to improve on the localization using the SEEKAT mulitbeam localizer[14] (Bezuidenhout et al., in preparation). This code compares the S/N of the detections of the various beams with the Point Spread Function (PSF) of the beam calculated using the MOSAIC software. The PSF will be dependent on the specific antennas used in the array during the observations, the position in the sky, and the frequency. We obtain the best improvement on the localization when we compare detections from different observations with different PSFs.

To facilitate the localization of the pulsars close to the centre of the cluster, we performed another observation on 2021 June 18 in L-band using 60 antennas with an average overlap of ∼ 0.85 covering only the central 1 arcmin with an observation time of 3.5 h. In this observation we were able to detect both J1823−3021I and J1823−3021J but only the first was detected in more than one beam. Using this observation, it was possible to improve the localization of J1823−3021I. The numerous detections of J1823−3021K in the two observations also allow a precise determination of its position. The best positions of the new pulsars are shown in Table 1 and in Fig. 3.

5 DISCUSSION

The TRAPUM pulsar searches in the GC NGC 6624 have resulted in the discovery of four new pulsars. For one of them, J1823−3022, the association with the cluster is not certain. The total number of pulsars with confirmed association in the cluster is now 11. All of the new pulsars discovered are isolated even though we searched also for binary pulsars. The pulsar population can therefore be divided into nine isolated pulsars and only two binaries. This result is quite unusual for a typical GC but it is common for core-collapsed cluster with a very high encounter rate per binary (Verbunt & Freire 2014) like NGC 6624. Another characteristic of GCs with high encounter rate per binary is the presence of mildly recycled pulsars that were disrupted before the spin-up process was completed. The newly discovered pulsar J1823−3021J with a period of 20.899 ms belongs in this category.

Verbunt & Freire (2014) also noted that in GCs with high encounter rate per binary a few pulsars tend to be located far from the central regions. Because of dynamical friction, the neutron stars would concentrate in the cores, but close encounters have the effect of displacing them. If the close encounters are frequent enough, there is a chance of observing a few pulsars while they are displaced before they drift back to the core. Thanks to the capability of TRAPUM to localize a pulsar in the cluster, Ridolfi et al. (2021) showed that this is true also in NGC 6624. Pulsar J1823−3021E has been found to be offset from the centre at a distance of roughly one half-light radius. This is further confirmed by the new discovery of J1823−3021K being located ∼1.4 times the half-light radius. These two pulsars have likely been involved in dynamical encounters that displaced them in the recent past and did not have time to fall back in the centre.

The newly discovered pulsars certainly associated with the GC are either too weak or too offset to be detected by the large number of observations made of the cluster using up to 44 antennas of MeerKAT with the PTUSE machines and we were not able to derive a timing solution for any of them. With further observations with more antennas it will be possible to find a timing solution for these discoveries. The measurement of the acceleration felt by the two new discoveries close to the centre, J1823−3021I and J1823−3021J, will be very helpful in testing the presence of the intermediate mass black hole claimed by Perera et al. (2017a).

Pulsar J1823−3022 is an intriguing new discovery. We do not have enough information to conclude whether the pulsar is associated with the GC. The period, period derivative, isolated nature, and position far from the centre of the cluster are more common features of the Galactic field pulsar population than the GC population. However, it is still inside the projected tidal radius of NGC 6624 and the cluster already contains two apparently young isolated pulsars with relatively high magnetic field strengths. The high period derivative and offset could be explained by a recent dynamical event that stopped the recycling and kicked the pulsar far from the cluster centre. Alternatively the pulsar could be born recently via the process of accretion-induced collapse (Lyne et al. 1996) or electron capture supernova (Boyles et al. 2011) and have received a kick. In order to determine the pulsar's association with the GC, further observations are needed. A measurement of the proper motion would verify if the pulsar's velocity through space is in agreement with the kinematics of the GC. The discovery of more pulsars associated with the cluster at a similar distance or DM of J1823−3022 could also help solve the mystery.

The discovery of J1823−3021K and J1823−3022, both with a very high positional offset from the centre, would not have been possible without the multiple beamforming capabilities and tiling patterns made available by TRAPUM. This shows that a significant number of interesting and potentially bright pulsars might still be waiting to be found in the outskirts of well-known clusters. Among the GC surveys currently in progress at the various telescopes around the world, TRAPUM has the best chances of finding and localizing these pulsars.

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[13] https://www.atnf.csiro.au/research/pulsar/psrcat/
[14] https://github.com/BezuidenhoutMC/SeeKAT

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DATA AVAILABILITY

The data underlying this article will be shared upon reasonable request to the MeerTime and TRAPUM collaborations.

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